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Design-Space Study of Low-Perigee Spacecraft

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Introduction

•NASA's Goddard Space Flight Center (GSFC) has begun a series of eight missions focused on the connection between the sun and earth's atmosphere. One of these missions is the Global Electrodynamics Connections (GEC) Mission.

•The University of Maryland has been asked to analyze and optimize the design of the probes in the GEC mission, doing so from an aerodynamic perspective and drawing on previous experience in the design and optimization of high speed shapes.

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GEC Mission

The theme of the mission is to establish the role of the ionosphere/thermosphere in the electrodynamic environment of near-Earth space. Within this context the GEC science objectives are:

1. To observe the magnetospheric energy transfer to the ionosphere and thermosphere by making space-time resolved observations in the transfer region.
2. To determine the key processes and their space-time scales for coupling between the ionosphere-thermosphere as magnetospheric energy is dissipated.

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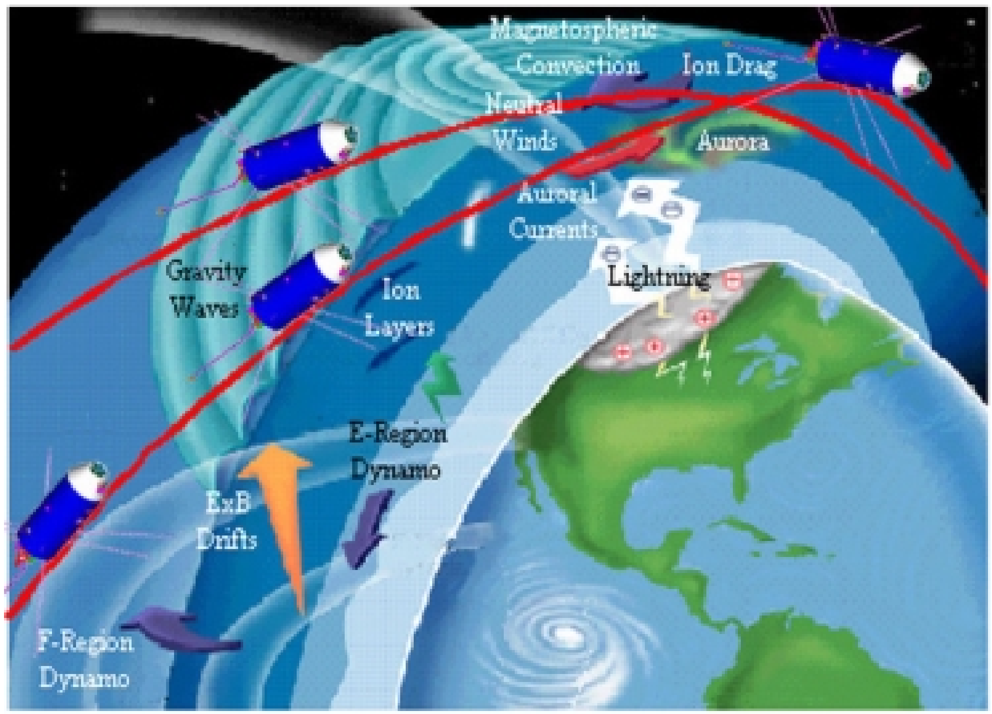
GEC Capabilities



- 4 “dipping” spacecraft reach as low as 120 km.
- Plane changes necessary
- Minimal disturbance of electromagnetic field
- Multiple (approximately 10) Earth passes

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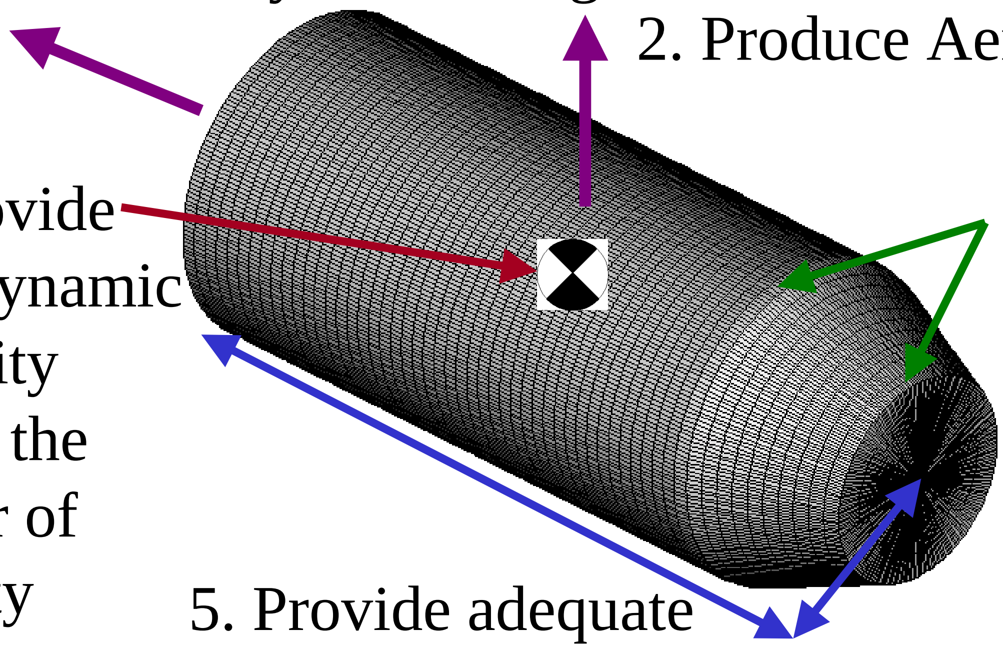
Design Constraints

1. Reduce Aerodynamic Drag

2. Produce Aerodynamic Lift

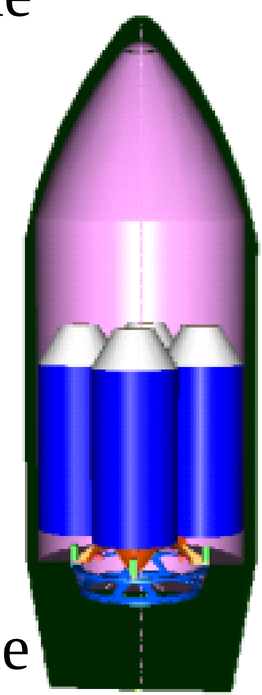


3.Minimize the number of small radius corners

4. Provide aerodynamic stability about the center of gravity

5. Provide adequate internal volume

6. Fit all four probes into the launch vehicle



Goals for Changing the Baseline Design

1. Reduce drag
   - Greater number of atmosphere passes
   - Less fuel needed
   - Lower perigee altitudes may be reached
2. Produce useful lift
   - Maneuvering capability without propulsion
   - Plane changes possible
3. Determination of forces relevant to formation flying
4. Stability

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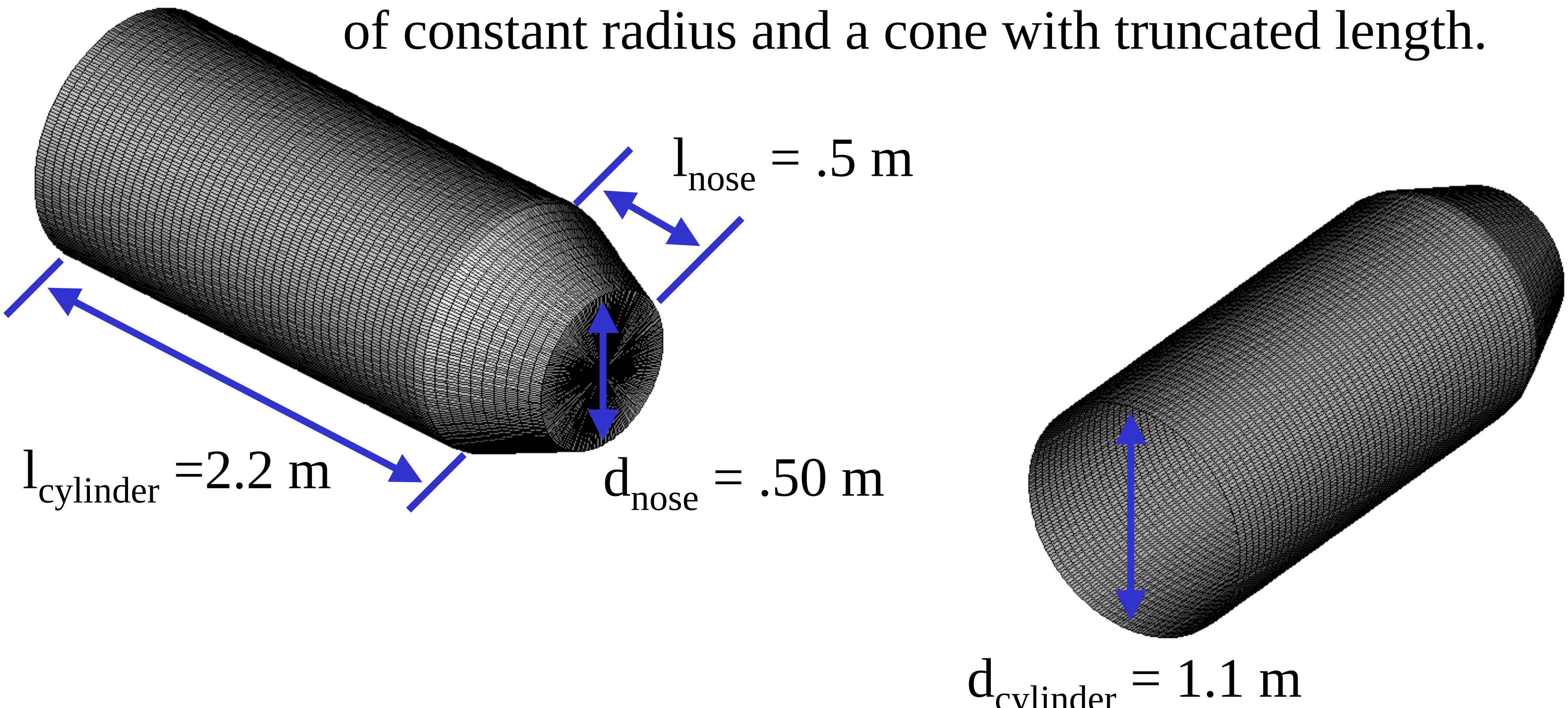
Baseline Geometry

GSFC’s current geometry is based upon a functional approach -- what instruments need to be on the probe and where those instruments need to be located. It uses a cylinder of constant radius and a cone with truncated length.



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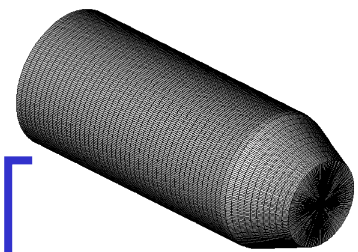
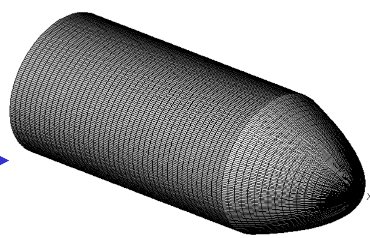
Changing the Geometry

In order to change the geometry from the current baseline design, we set forth an initial plan that changed only the nose to a power law shape (1). Next we allowed the body to become non-cylindrical by giving it a full power-law shape (2). Finally, the body was given a hyper-elliptical shape capability (while still maintaining the power-law length constraint) (3).



(1)



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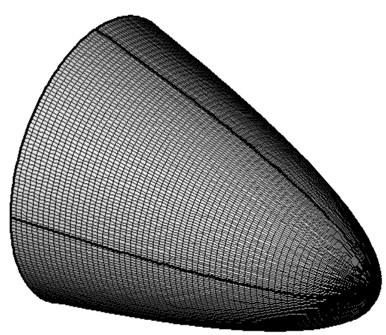

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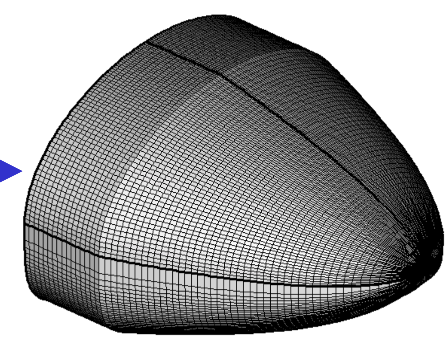

New Geometry Nose Model

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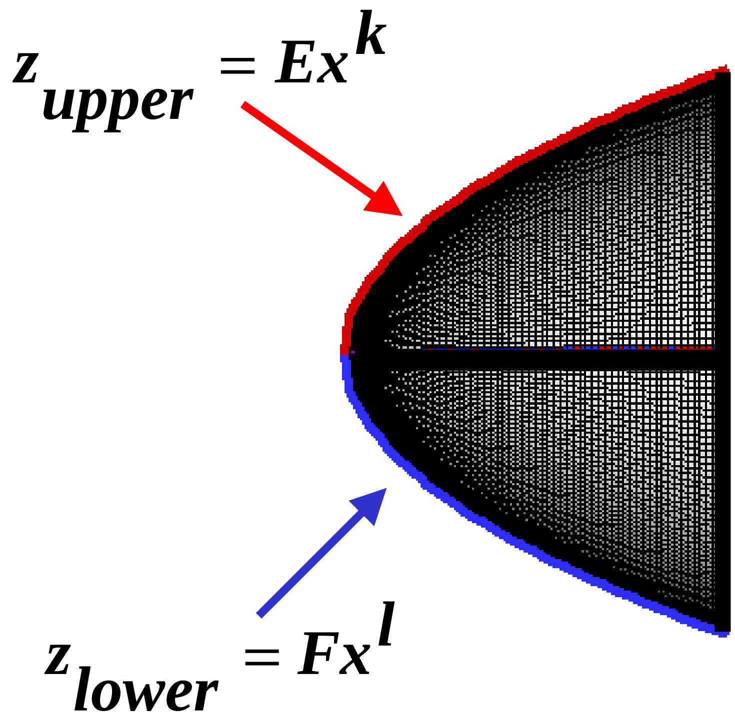
The new geometry model will attempt to bring an aerodynamic perspective to the design. Previous work has shown that minimum drag, high speed bodies are approximately power law shaped. Thus, power laws are used here to govern the shape of the nose in the axial direction.



4 design variables (E,F,k,l) govern the nose

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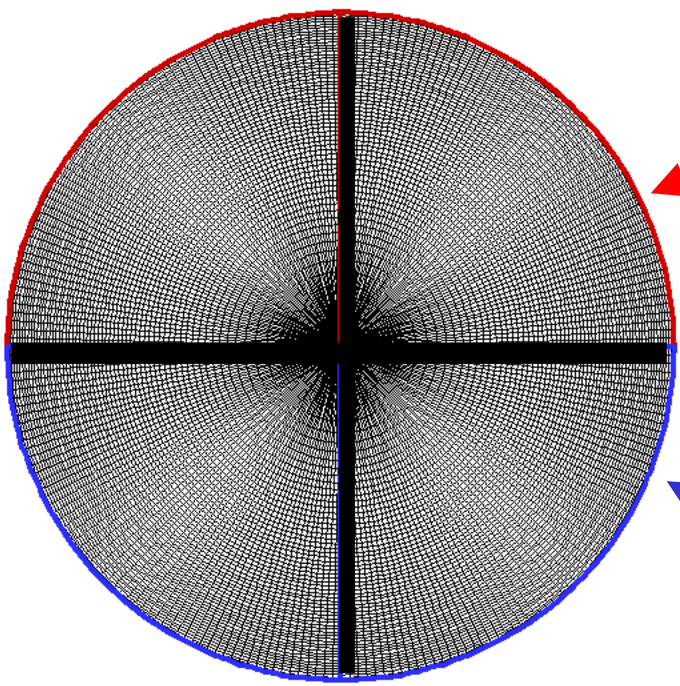
New Geometry Cross-section Model

In order to provide lift, the cross-section must move away from the current design of a circle. We have employed here a hyper-ellipse on the upper surface and a super-ellipse on the lower surface in order to allow a variety of cross-section shapes.



$$\left|\frac{z_{upper}}{a}\right|^{m}+\left|\frac{y_{upper}}{b}\right|^{m}=1$$

$$eccentricity = e = \frac{a}{b}$$

$$z_{lower} = r_z\left[1-\left(\frac{y_{lower}}{r_y}\right)^{\frac{2}{n}}\right]^{\frac{n}{2}}$$

3 design variables (m,n,e) govern the cross-section shape

a, b, r_z, r_y are functions of the boundary conditions

Complete New Geometry Model

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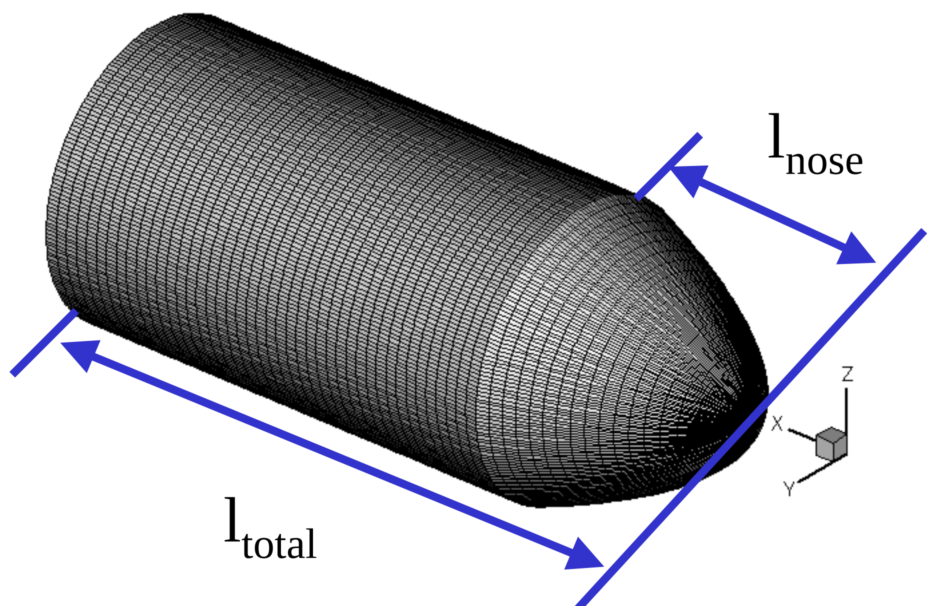
The final geometry generator uses 9 variables to describe a single shape. These shapes range from blunt-to-sharp noses and concave-to-circular-to-convex cross-sections.

4 nose variables

3 cross-section variables

+ 2 length variables

9 total geometry variables



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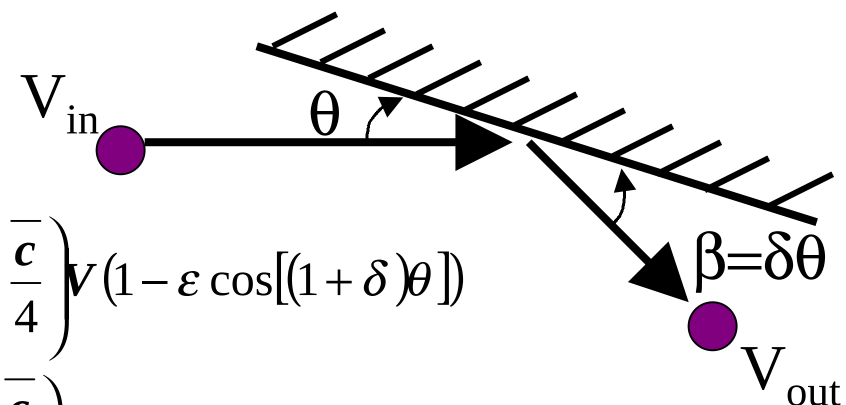
Aerodynamic Model

The aerodynamic model is based upon the momentum transfer of particle-surface interaction. Using this method, coefficients of rebound-to-impact velocity (ε) and angle (δ) can be quickly formulated. Total accommodation of the gas particles occurs for {ε, δ}=0 and specular reflection occurs for {ε, δ}=1.



$$\frac{\boldsymbol{Drag}}{\boldsymbol{Area}} = \rho\left(\boldsymbol{V}\sin\theta + \frac{\bar{\boldsymbol{c}}}{4}\right)\boldsymbol{V}\left(1 - \varepsilon\cos[(1+\delta)\theta]\right)$$

$$\frac{\boldsymbol{Lift}}{\boldsymbol{Area}} = \rho\left(\boldsymbol{V}\sin\theta + \frac{\bar{\boldsymbol{c}}}{4}\right)\boldsymbol{V}\varepsilon\sin[(1+\delta)\theta]$$

$\rho \equiv$ density $\quad \bar{\boldsymbol{c}} \equiv$ thermal velocity $\quad \boldsymbol{V} \equiv$ velocity magnitude

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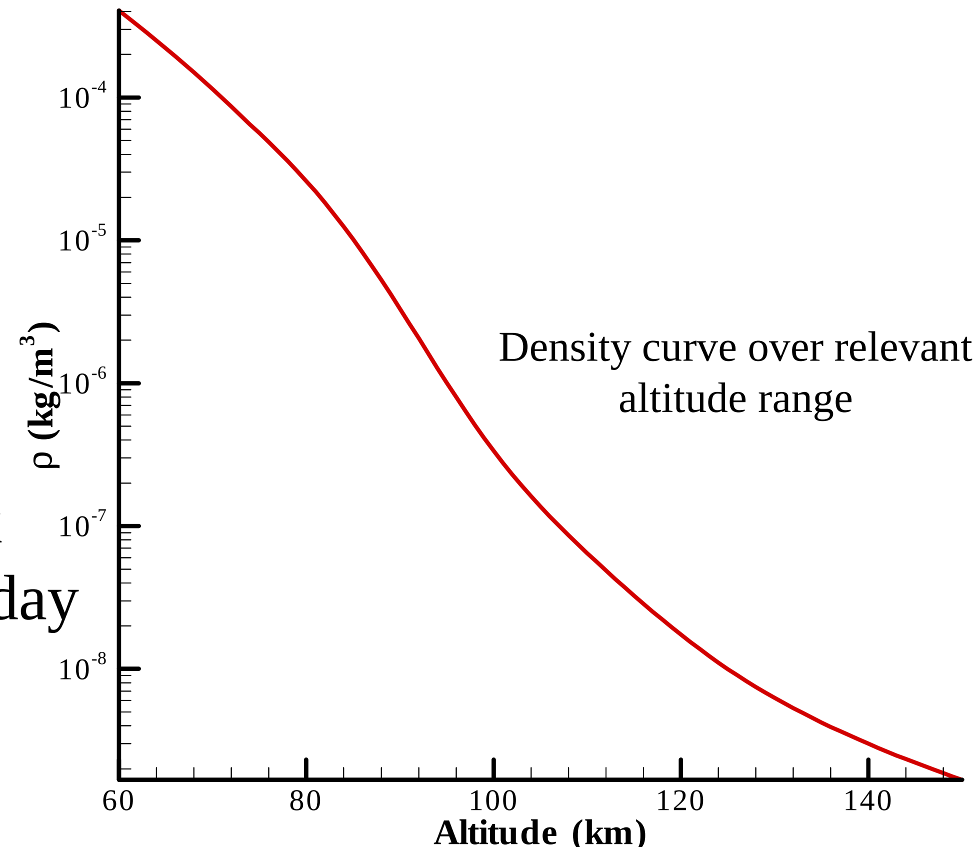
Atmosphere Model

The atmosphere model used is the MSISE90 model which is valid from sea-level to 1000 km. This model takes into account the following factors:

- Day of year
- Altitude
- Universal time
- Geodetic latitude
- Geodetic longitude
- Local apparent solar time
- 3-month average of F10.7 flux
- Daily F10.7 flux for previous day
- Magnetic index



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Results: Methodology

Because this is an initial study of the optimization design space, we have elected to change the original geometry only slightly. In doing so, we will answer the following questions:

1. Does the aerodynamic model come close to expected results?
2. How does a same-length power-law nose compare in drag to the original geometry?
3. How does a same-volume power-law nose compare in drag to the original geometry?
4. How does drag affect the spacecraft's ΔV during atmospheric passes?

Aerodynamic Model vs. Expected Results

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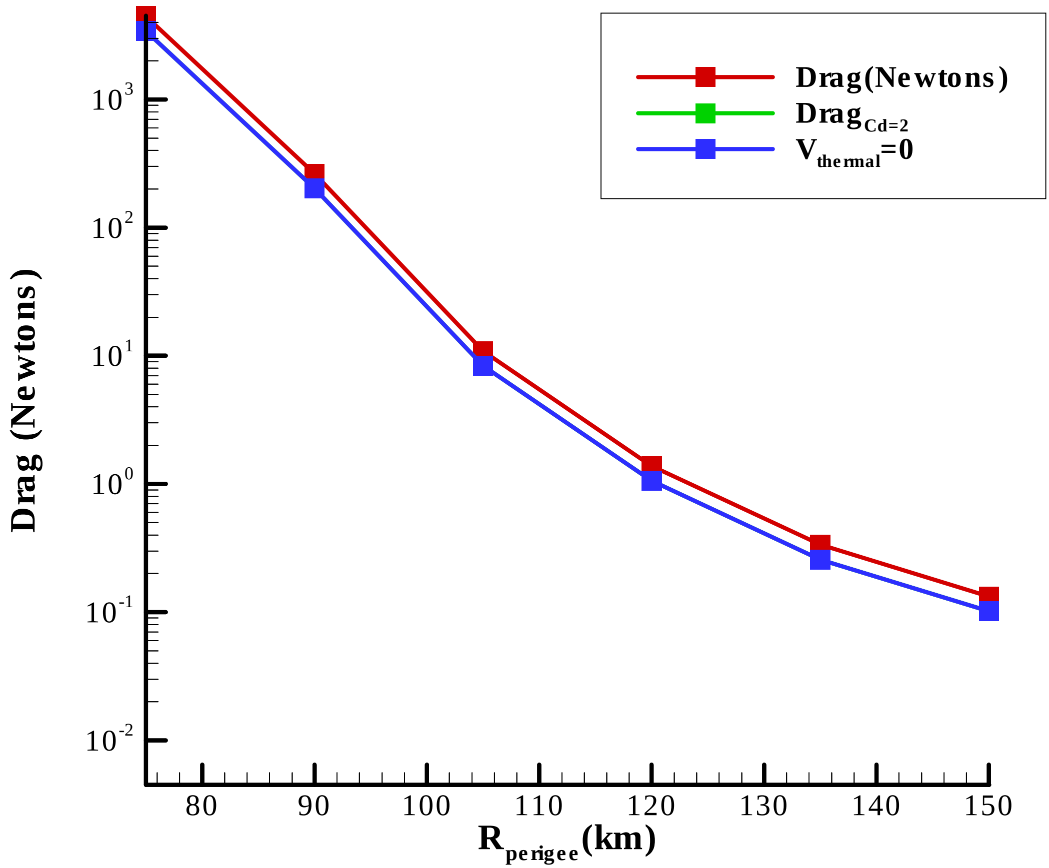
When the accommodation conditions are assumed to be total (ε, δ=0), drag should be a function of the surface area normal to the flow with some increase from the thermal velocity component and the coefficient of drag should equal 2. As seen from this plot, our aerodynamic model correctly calculates the drag for total accommodation. The exact line (green) is hidden by the blue line (thermal velocity equals 0). The actual drag (red) is slightly higher due to thermal velocity.



Length-matched Power-law nose

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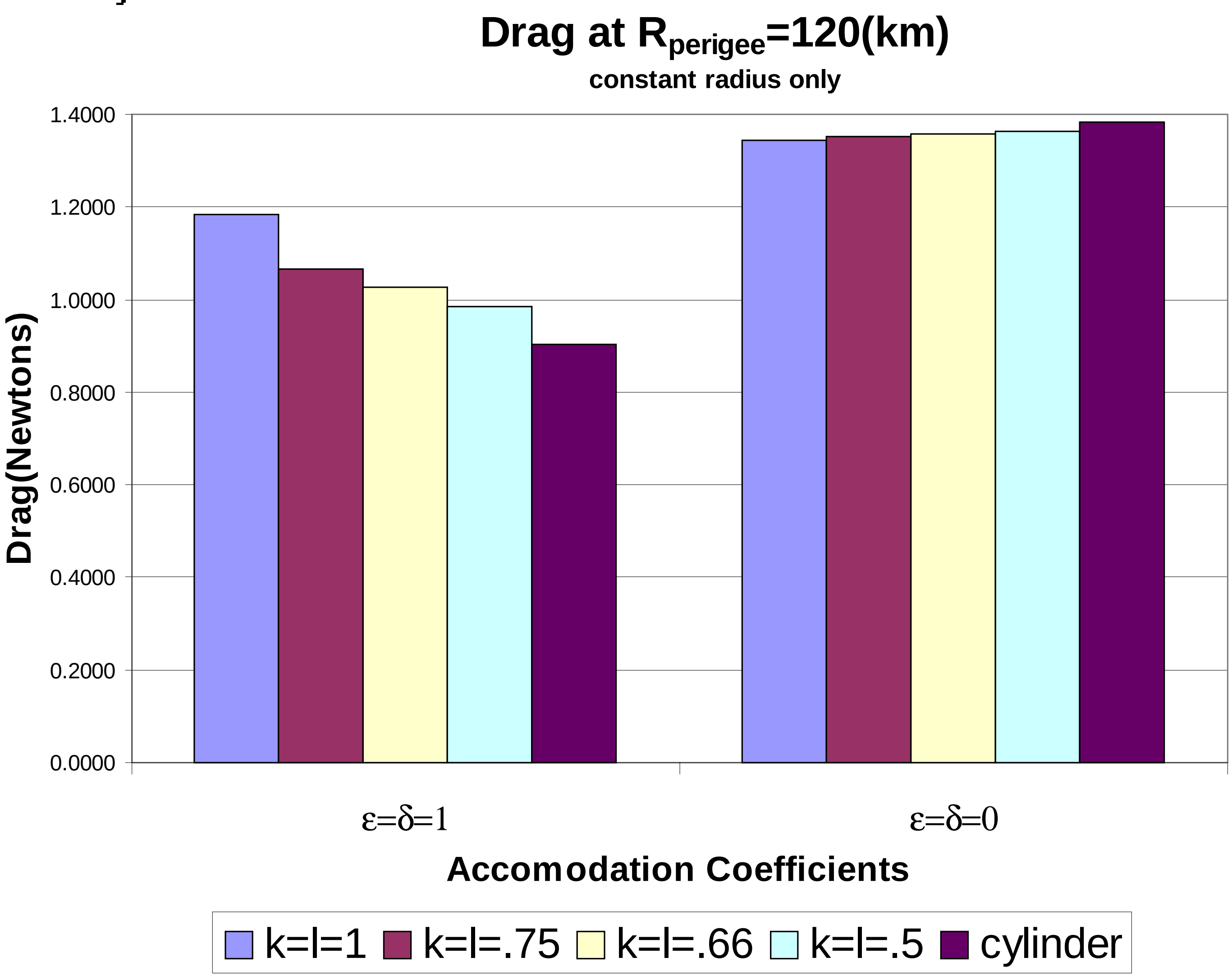

The original truncated nose is replaced with power law values of .5, .66, .75, and 1. The length (l_{nose}) is the same as the cone and altitude is 120 km.

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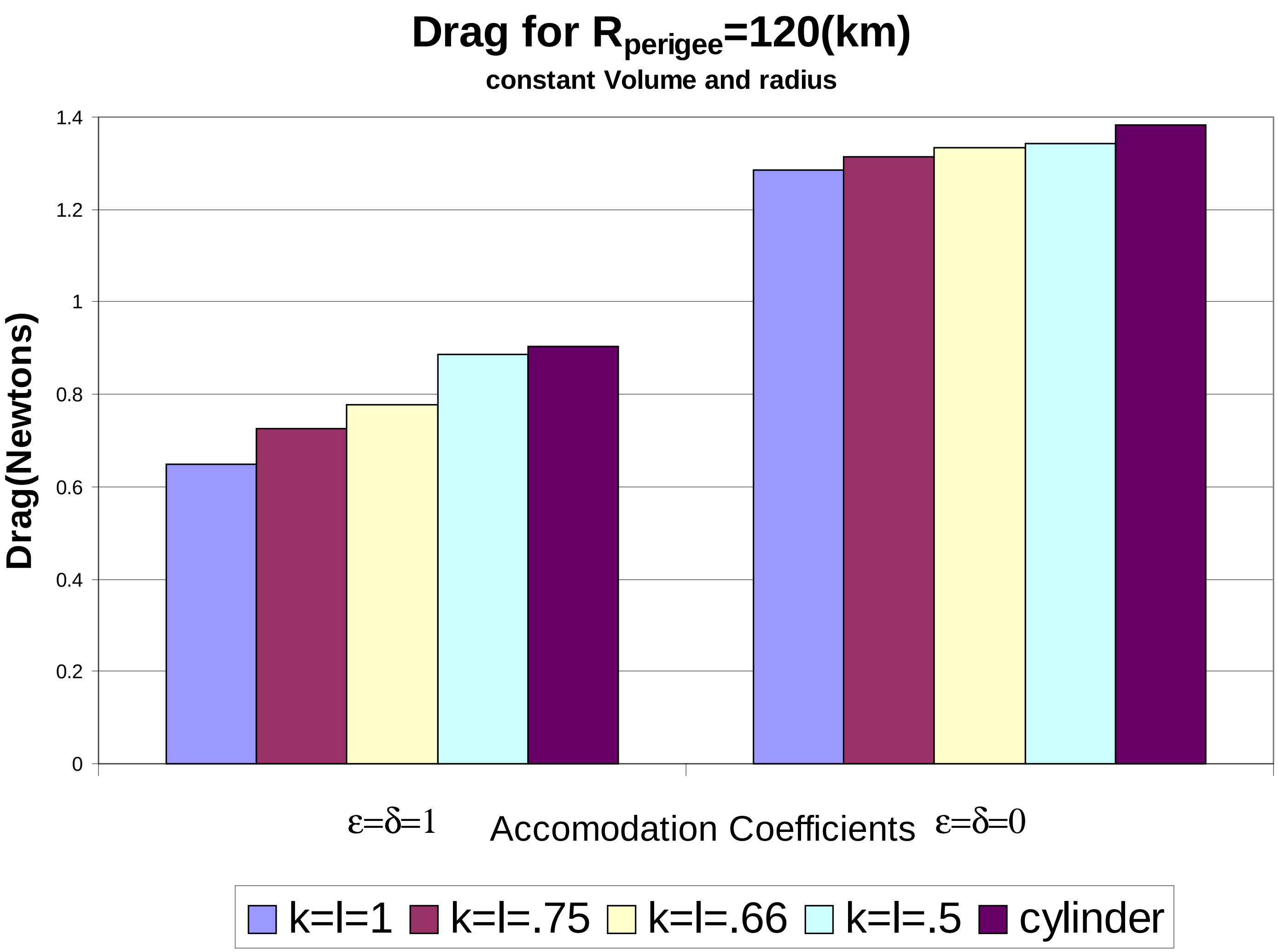
Volume-matched Power-law nose



The original truncated nose is replaced with power law values of .5, .66, .75, and 1. The length (l_{nose}) is allowed to vary, but the volume is the same as the original geometry. Altitude is 120 km.

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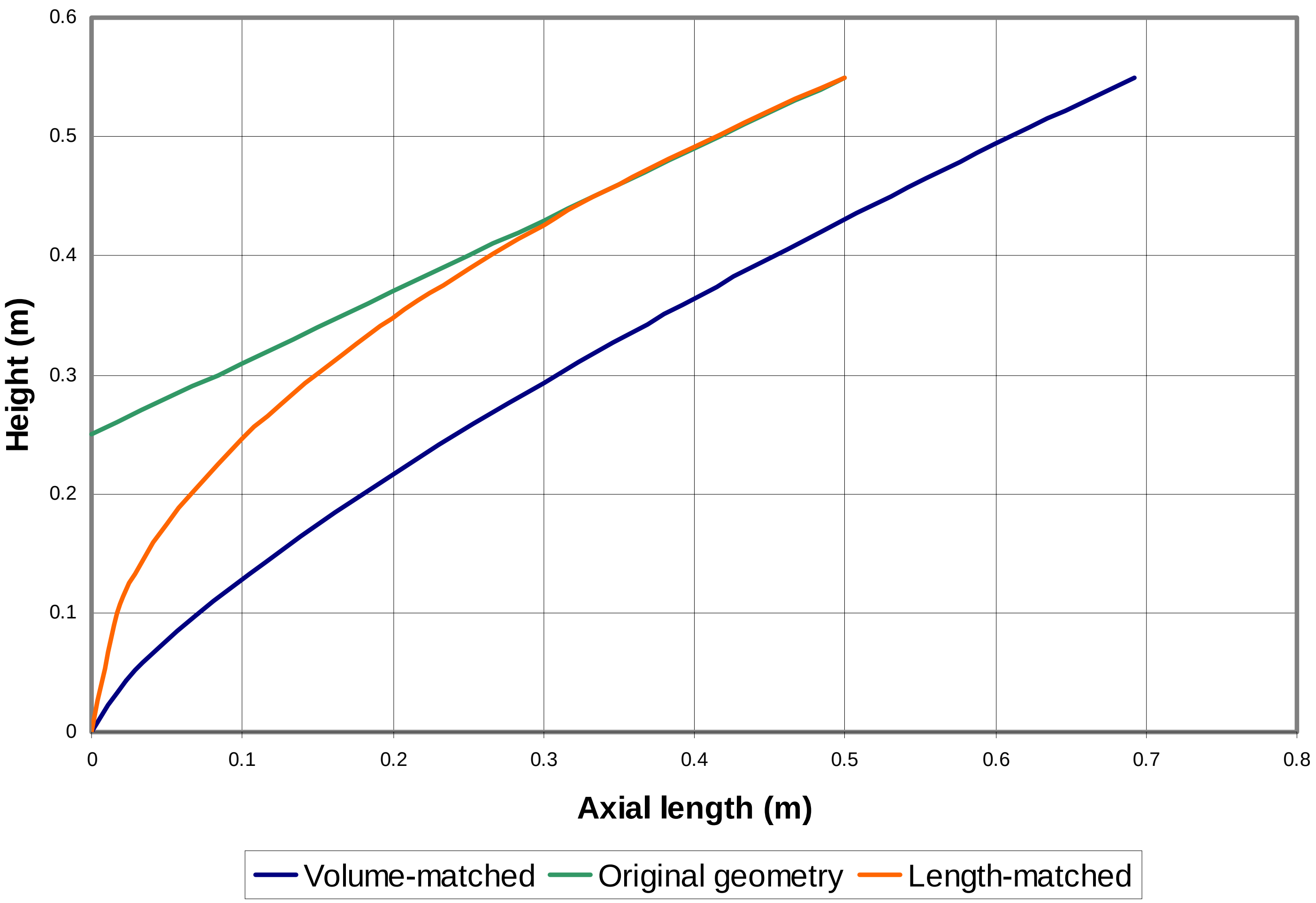
Nose Shape Comparison



In order to match the volume of the original nose geometry, the length of the nose grew. This plot shows the volume matched geometry and the length-matched geometry for a power-law value of 3/4 .

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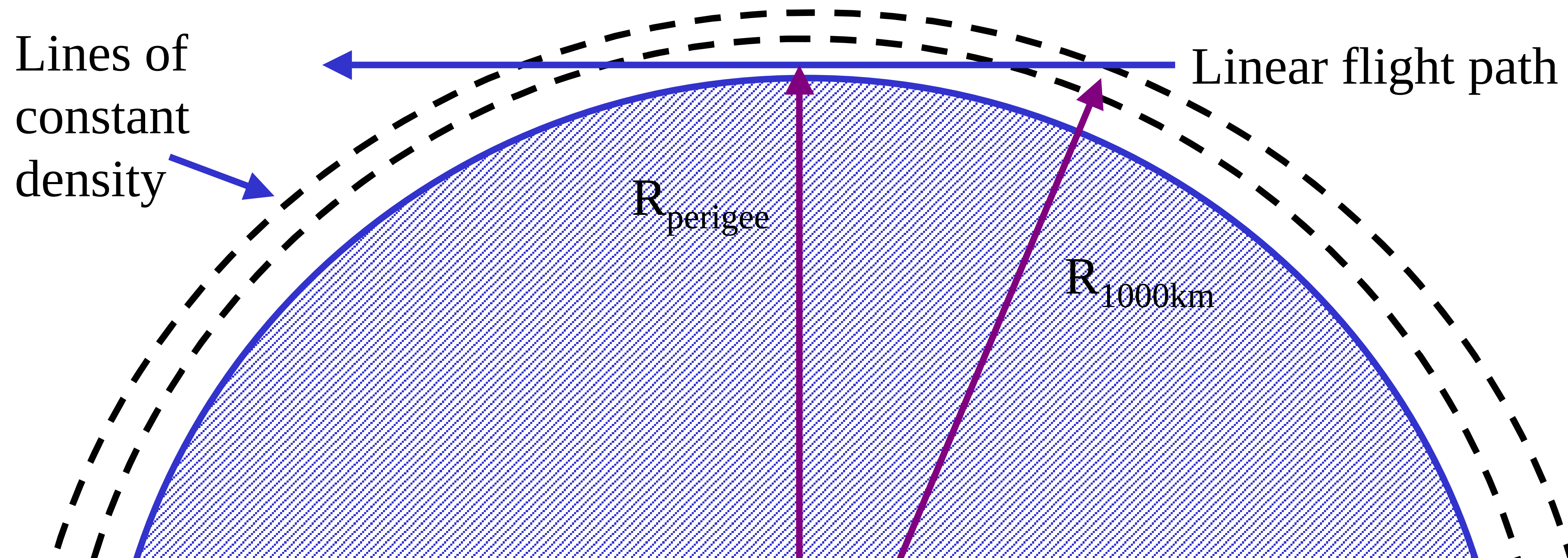
ΔV_{loss} Calculations

As a conservative estimate, a linear path through the atmosphere was assumed in order to find to the total velocity lost due to drag during the atmospheric passes. The drag calculations began at 1000 km and the perigee was varied from 150 km to 75 km.



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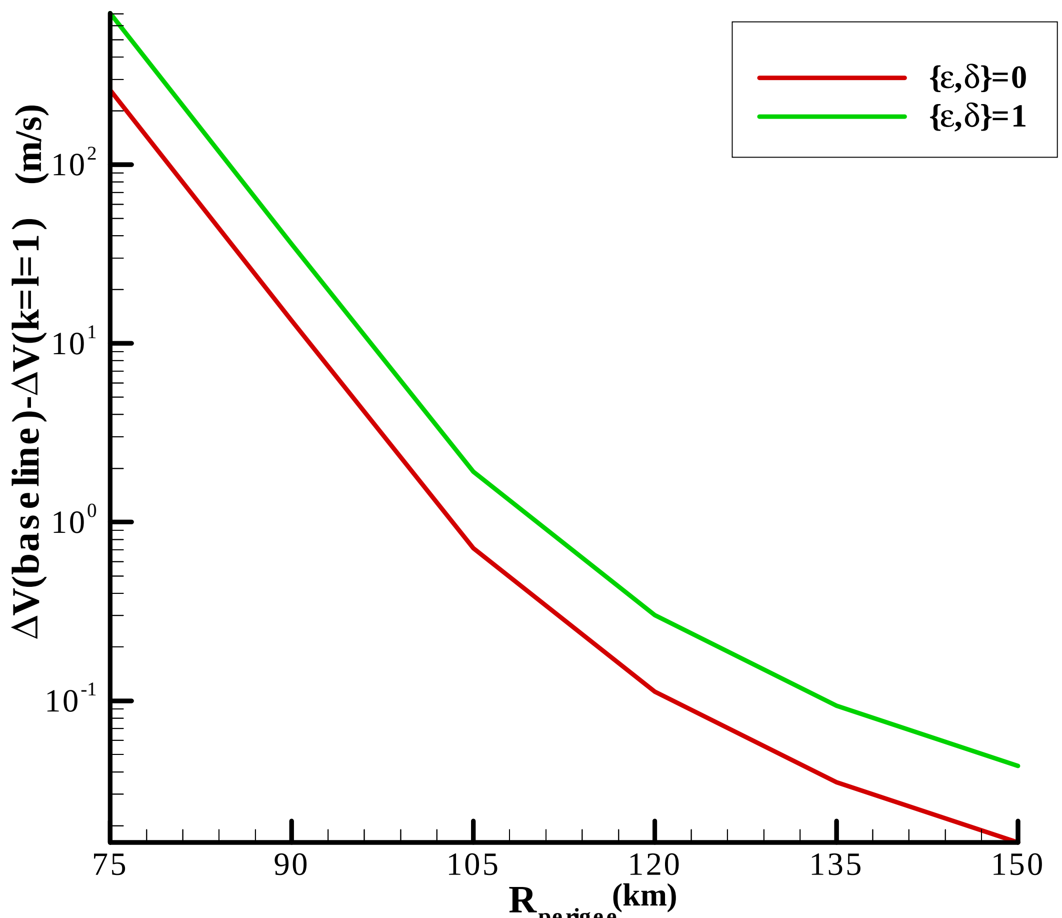
ΔV_{loss} Results



In order to bound the ΔV_{loss} results, the difference in ΔV_{loss} between the original configuration and our lowest drag configuration (volume-matched nose with power of 1) is plotted for conditions of total accommodation and specular reflection. It is seen here that the performance is better as the accommodation approaches specular.

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Conclusions

- Gas accommodation conditions are very important for drag calculations.
- For minimum drag, a length-matched power-law nose may work if the accommodation is close to total.
- The volume-matched power-law noses will produce lower drag especially for specular accommodation conditions, but there seems to be no optimum since the drag decreased consistently as the power-law values approached 1.
- The ΔV_{loss} comparison confirmed that the performance of the volume-matched power-law is best as accommodation approaches specular. It also seemed to place tight bounds on the total possible ΔV savings available from lower drag geometries. However, it is expected that a full optimization of all the design variables will make the ΔV bounds much less rigid.

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Future Work

Future work will include the following:

•Further validation of the aerodynamic model

•More complicated geometries will be considered

•Full numerical optimization for various objective functions including minimum drag, maximum lift, and maximum volume within the design constraints